CUDOs and their impact (literal and figurative)

Johann Rafelski

Something STRANGE is sometimes hitting planetary bodies – Where is the meteorite? Maybe it went into the Earth? We consider compact ultra-dense objects (CUDO) meteors made predominantly of ultra dense matter such as STRANGElet = fragments of neutron stars filled with strange quarks, DARK MATTER bound objects, MICRO BLACK HOLES. For such exotic impactors each planet or moon is a macroscopic detector accumulating CUDO impact signature over geological time scale. Only a fraction of the CUDO kinetic energy is damaging the entry/exit surface regions since CUDOs high density of gravitating matter assures surface-penetrating puncture – shot into, and even through.

Major consequence for climate.

CUDOs maybe recognized by impact (exit) features, recent work suggests distinctly different crater morphology. In case of Earth impact we are interested in impactor exit =volcano(?!?) accompanied by a major climatic excursion. Rocky objects in solar system accumulate CUDO impact scars for billions of years. Asteroid belt could harbor captured CUDOs with 31 Polyhymnia a high density (75g/cc!) candidate and the "egg in space" offering another suspect case.
Most matter in the Universe unknown  
Dominant content of the Universe and  
Origin of baryon asymmetry remain a mystery

The contents of the Universe today  
(fractions change ‘rapidly’ in expanding Universe)

1. Visible (baryonic) matter: mainly hydrogen, helium  
   (less 5% of present day total energy inventory)  
   A mere $10^{-9}$ remnant of post QGP baryon annihilation period

2. Free-streaming matter  
i.e. particles that do not interact – have ‘frozen’ out:
   - Photons: since $T = 0.235 \text{eV}$ (insignificant in today’s inventory)
   - Neutrinos: since $T = 1.5–3.5 \text{MeV}$
   - Mystery dark matter (25% in energy inventory)
     1. Massive ColdDarkMatter free from way before QGP hadronization  
     2. Warm dark matter: e.g. neutrinos of suitable mass  
Domination eras of different forms of energy

The Universe Composition in Single View

Different dominance eras

dark energy  matter  radiation  $\nu, \gamma$  BBN+leptons  hadrons
**Dark Matter is Matter**

From standard cosmology, fractions of Non-Baryonic and Baryonic gravitating matter show $4/5$ of gravitating matter not identified: ‘dark’

Bullet Cluster, Abell 520, etc show – Separation of luminous matter and gravity source
⇒ evidence of independent dynamics
⇒ small self-interaction

Many candidate particles could mean *many components of unseen ‘dark’ matter,*
Self-interacting dark matter—a hypothetical form of dark matter made of particles that interact with one another—is a problem fixer in cosmology. On galactic and smaller scales, it can fix discrepancies between observations and predictions of the standard cosmological model, which instead considers “cold” dark matter that doesn’t interact with itself. And it does so while leaving intact the standard model’s success on larger scales. Manoj Kaplinghat from the University of California at Irvine, Hai-Bo Yu from the University of California at Riverside, and colleagues now show that self-interacting dark matter can also explain the diversity of galaxy rotation curves—graphs of the speeds of stars in a galaxy versus their distance from the galaxy’s center.
Normal matter iron-20%nickel impactor Gebel-Kamil crater: Uweinat Desert, Egypt: 44.8m in diameter, 15.8m deep meteorite crater: 1600 kg of iron meteorite shrapnel, 3400 kg >10 g pieces remained today. Upon hypervelocity impact, the 1.3 meters wide 5 to 10 tons meteorite was disrupted into thousands of fragments located up to 200 m from the crater rim, largest known fragment 83 kg. Dated to about 4,500 years, explored first 2009/10. A possible source of Egypt-Pharaoh Iron.
Where is the Meteorite that made Arizona Meteor ‘Barringer’ Crater?

This is about 1 mile wide and 570 ft deep recent (50,000y old) crater where many tourists in Arizona visit. 110 years ago Daniel Barringer searched to profit from what he expected to be $2.5 \times 10^6$ tons of iron-nickel content of the meteorite. See what was found: a few (3!) meteorite fragments found in riverbeds many miles away. Short of a space ship crash site, of which remains were carefully removed, what is the causes for this gigantic hole in the ground? There are many other “missing meteorite” impacts.
Missing meteorite case is not singular

Meteor crater

1.2km diameter/50ky old

Pingualuit crater in Nunavik, northern Quebec, Canada, looking west.


3.44 km diameter $1.4 \pm 0.1 \times 10^6$y old

Lonar crater:1.8km, 15,000y? hole in basalt flow from 50 million years ago.....
Are there impactors that cut into/across a planet?

Must be made of very dense matter which cannot be supported by surface tension. CUDOs (compact ultradense objects) loose energy along the path inside target - not on impact. Scenario example: collision with cold dark matter sitting still in the Universe through which we plough across with nearly 300 km/s – a shot across the Earth is the result. Such a CUDO would be a remnant of Universe birth. Certainly not a frequent event. But consequences for Earth very special:

- Impact-exit ionospheric deposit of material = Climate Winter
- Possible raining of matter (spherules)
- Mantle damage=Hot spots, continent breakup etc.

Also, some chance to capture shoot-through CUDOs inside Earth or more generally the Solar system: so we do not only look at craters, climate, but at what is flying now in Solar system, and even Earth’s energy balance.
Exit shot through model: Shot across glass plate

Glass shot from: Fig 1 b from Nicolas Vandenberghe, Romain Vermorel, Emmanuel Villermaux. “Star shaped crack pattern of broken windows” Physical Review Letters 110 174302 (2013)
Mojave Crater on Mars: Source of 80% Mars impactors on Earth – 55km large ‘recent crater’

...55-kilometer-wide Mojave crater on Mars formed 3-5 million years ago. Based on their cosmic ray exposure, the shergottites from Mars must have broken off between 1 and 5 million years ago. Prior confusion on dating due to melting; this supports CUDO hypothesis. Note rayed structure.

The Source Crater of Martian Shergottite Meteorites

Sourcing Martian Meteorites

There are nearly 150 recognized martian meteorites, but where exactly they came from on Mars is not known. Werner et al. (p. 1343, published online 6 March) present evidence that the <5 million-year-old Mojave impact crater on Mars is the single ejection site of one type of martian meteorites: the shergottites. The Mojave crater formed on an ancient terrain on Mars, and so the shergottites represent old martian crustal material.
A dramatic Mars impact crater created between July 2010 and May 2012 photographed by HiRISE camera on board NASA’s Mars Reconnaissance Orbiter on Nov. 19, 2013. The 30 meters in diameter crater is surrounded by a 15km large, rayed blast zone.
Fig. 9. The largest and aligned shield volcanoes in the Mars Tharsis Montes region are Ascraeus Mons, Pavonis Mons, Arsia Mons (on diagonal line), and Olympus Mons (off in NW corner). Arsia Mons has the largest caldera on Mars, having a diameter of 120 km. The main difference between the volcanoes on Mars and Earth is their size; volcanoes in the Tharsis region are up to 100 times larger than those anywhere on Earth. Detailed photography by University of Arizona LPL HiRISE of Pavonis Mons reveals a giant central conical and unexplained cave, see text for more detail. Photo: Sources NASA, University of Arizona/LPL, Arizona State University.
CUDO structure candidates

1. Stable fragments of neutron stars = nuclear ‘strangelets’
2. Dark matter starlets
   (self-interacting DM; maybe gravity bound DM)
3. Micro black holes

NOTE: Depending on primordial, or galactic origin, relative speed vastly different; the frequency of collision very different, mass of impactors very different. Morphology of impactor (exit) scars seen in Solar system suggest ALL of the above has happened.
Collisions: Stopping, Other Characteristics

Entrainment of Material
Captured matter acquires CUDO velocity ⇒ reduces CUDO speed, damage in target also reduces speed Expect ⇒ Two surface punctures! Entry and Exit signatures

Drag from Normal matter interactions
► Mixing of nearby entrained and nearly-entrained material

Pulling debris stream along behind CUDO
► Matter from previous collisions can “dress” CUDO, giving appearance of normal (but overdense) meteor
► Fraction remains bound to impacted planet, but re-distributed inside and above surface
Our arguments are published\&arXiv-ed

Work by other groups will be cited in text

*Compact ultradense matter impactors*
http://prl.aps.org/abstract/PRL/v110/i11/e111102

*Compact Ultradense Objects in the Solar System*

*Properties of Dark Compact Ultra Dense Objects*
http://dx.doi.org/10.1016/j.physletb.2012.02.015

*Planetary Impacts by Clustered Quark Matter Strangelets*
http://dx.doi.org/10.5506/APhysPolBSuppl.5.381

*Classification of exoplanets according to density*
A. Odrzywolek and JR
http://dx.doi.org/10.5506/APhysPolB.49.1917
Primordial DM Meteor Possible? – Qualitative Consideration

High mass/energy scale help with early-universe formation:

- Becoming non-relativistic at an earlier time, heavy dark matter particles have a local high density allowing gravity to amplify local density fluctuations (dark matter helps visible matter assemble rapidly)

- CUDO comprises $10^{11} - 10^{19}$ fewer particles $\Rightarrow$ requires smaller correlation volume contributing

- Dark particle-particle gravitational interaction $10^6 - 10^{10}$ times larger maybe capable to ‘kick out’ visible matter to tightly bind.

- High surface acceleration CUDOs stable against gravitational disruption (especially in collisions with normal matter objects) $\Rightarrow$ persist into present era nearly at rest in CBM frame of reference.
Dark impacts and CLIMATE excursions: 1) AD 536 Event


...cause is contested: a comet or a giant volcano (not found) eruption. The 6-month (time measurement resolution) dual event coincidence has probability $10^{-3}$. Can be more naturally explained by a dressed CUDO puncture and associated transport of material into upper atmosphere.

2) Other recent climate fluctuations are also not well understood: BBC: *It was 10 October 1465 - the day of the wedding of King Alfonso II of Naples ... middle of the day, the Sun had turned a deep azure, plunging the city into eerie darkness ...* Four years later, Europe was hit by a mini ice age... It was the biggest eruption for 700 years but scientists...
The massive volcano that scientists can’t
It was the biggest eruption for 700 years but scientists still can’t find the volcano responsible.

It was 10 October 1465 – the day of the highly anticipated wedding of King Alfonso II of Naples. He was set to marry the sophisticated Ippolita Maria Sforza, a noblewoman from Milan, in a lavish ceremony.

The thing is, scientists can’t find the volcano that did it. What’s going on?

produced an ash cloud which enveloped the Earth and led to the coolest decade for centuries.

This is a true geological mystery, which has left geologists scratching their heads for decades.

Though it was the middle of the day, the Sun had turned a deep azure, plunging the city into eerie darkness.

This was just the beginning. In the months that followed, European weather went haywire. In Germany, it rained so heavily that corpses surfaced in cemeteries. In the town of Thorn, Poland, the inhabitants took to travelling the streets by boat. In the unrelenting rain, the castle cellars of Teutonic knights were flooded and whole villages were swept away.

Four years later, Europe was hit by a mini ice age.

That the ‘unknown eruption’ happened is undisputed – like most mega-eruptions, it vapourised vast quantities of sulphur-rich rock, which was blasted into the atmosphere and eventually snowed down on the poles as sulphuric acid. There it was locked into the ice, forming part of a natural record of geological activity that spans millennia. There’s no other event capable of doing this, short of an asteroid impact.

ALSO reported by Janus Pannonius, a poet of King Matthias of Hungary. Source: http://mek.oszk.hu/06700/06722/06722.htm#975 (Thanks to Prof. László Szarka)
Groenland temperatures

![Graph showing temperature changes over centuries]

Years Before Present (1950)

Temperature (°C)

11000 10000 9000 8000 7000 6000 5000 4000 3000 2000 1000 0

-33.0 -32.5 -32.0 -31.5 -31.0 -30.5 -30.0 -29.5 -29.0 -28.5 -28.0

8.2 kYr Event
Spherules

How did an impact distribute these spherules, that is the question here!

Evidence for deposition of 10 million tonnes of impact spherules across four continents 12,800 y ago

James H. Wittke\textsuperscript{a}, James C. Weaver\textsuperscript{b}, Ted E. Bunch\textsuperscript{a,\textdagger}, James P. Kennett\textsuperscript{c}, Douglas J. Kennett\textsuperscript{d}, Andrew M. T. Moore\textsuperscript{e}, Gordon C. Hillman\textsuperscript{a}, Kenneth B. Tankersley\textsuperscript{\textdagger}, Albert C. Goodyear\textsuperscript{b}, Christopher R. Moore\textsuperscript{f}, I. Randolph Daniel, Jr.\textsuperscript{g}, Jack H. Ray\textsuperscript{h}, Neal H. Lopinot\textsuperscript{i}, David Ferraro\textsuperscript{j}, Isabel Israde-Alcántara\textsuperscript{m}, James L. Bischoff\textsuperscript{n}, Paul S. DeCarli\textsuperscript{p}, Robert E. Hermes\textsuperscript{p,\textdagger}, Johan B. Kloosterman\textsuperscript{q,\textdagger}, Zsolt Revay\textsuperscript{q}, George A. Howard\textsuperscript{q}, David R. Kimbel\textsuperscript{r}, Gunther Klettetschka\textsuperscript{s}, Ladislav Nabelek\textsuperscript{t,\textdagger}, Carl P. Lipo\textsuperscript{w}, Sachiko Sakai\textsuperscript{w}, Allen West\textsuperscript{w}, and Richard B. Firestone\textsuperscript{w}

Fig. 1. YDB impact field, based on data from 27 locations. In the YDB strewnfield (red), there are 18 YDB sites in this study (red dots; see table on Right). Eight independent studies have found spherules and/or scoria-like objects at nine additional sites (blue dots) located in Arizona, Montana, New Mexico, Maryland, South Carolina, Pennsylvania, Mexico, and Venezuela. The largest accepted impact strewnfield, the Australasian (purple), is shown for comparison with each strewnfield covering ~50 million square kilometers or ~10% of the planet. Table shows location of sites and lists site details (A, archeological material; B, black mat; C, charcoal; M, megafaunal remains, present either at the sampling location or in the vicinity). Also given are stratigraphic settings (Strat: A, alluvial; C, colluvial; E, eolian; G, glacial; and L, lacustrine) and relative physical stability of depositional paleoenvironments (Env: A, active, e.g., riverine, lacustrine, or eolian; I, inactive).
Some Earth puncture crates a lasting damage that cures slowly

Hawaii is a ‘hot-spot’: the central pacific plate moving NW over the deep hot spot giving birth to chain of a dozen islands (edge: next slide)
Plume may be (nearly) stable

The edge in island ridge explained to be dominated by plume dynamics implies plume stable over 50 million years. WHY?

The Bent Hawaiian-Emperor Hotspot Track: Inheriting the Mantle Wind

John Tarduno, Hans-Peter Bunge, Norm Sleep, Ulrich Hansen  3 APRIL 2009 VOL 324 50

Bends in volcanic hotspot lineaments, best represented by the large elbow in the Hawaiian-Emperor chain, were thought to directly record changes in plate motion. Several lines of geophysical inquiry now suggest that a change in the locus of upwelling in the mantle induced by...
Global distribution of the 61 hot-spots listed in https://en.wikipedia.org/wiki/Hotspot_(geology); Eurasian Plate:
Eifel hotspot (8) 50°12’N 6°42’E, w= 1 az= 082° ±8° rate= 12 ±2 mm/yr
Iceland hotspot (14) 64°24’N 17°18’W
Azores hotspot (1) 37°54’N 26°00’W
Jan Mayen hotspot (15) 71°N 9°W Hainan hotspot (46) 20°N 110°E, az= 000° ±15°
Hot Spots provide lasting (50mY) reference frame

The Geological Society of America
Special Paper 430 2007

Plate velocities in the hotspot reference frame

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We present a table giving the “present-day” (average over most recent ~5 m.y.) azimuths of tracks for fifty-seven hotspots, distributed on all major plates. Estimates of the azimuth errors and the present-day rates for those tracks with age control are also given. An electronic supplement contains a discussion of each track and references to the data sources. Using this table, the best global solution for plates moving in a fixed hotspot reference frame has the Pacific plate rotating about a pole at 59.33°N, 85.10°W with a rate that gives a velocity at this pole’s equator of 89.20 mm/yr (~0.8029 °/m.y.). Errors in this pole location and rate are on the order of ±2°N, ±4°W, and ±3 mm/yr, respectively. The motions of other plates are related to this through the NUVEL-1A model.
Some hot spots coincide with gravitational anomalies (mascons)

A mass concentration (or mascon) is a region of a planet or moon’s crust that contains a large positive gravitational anomaly.
Moon gravity anomalies

Gravity map of the Moon by GRAIL

lunar Mare Smythii Topography

gravity
Kimberley open pit diamond mine coincides with

negative mascon - ‘made(??) by asupersonic gas ejection’
Have CUDOs been captured: Earth energy balance

We begin to recognize that Earth heat radiance estimated at 44.2 TW is out of balance: we radiate about 2-3 times the amount produced radiogenically.

Extreme condition measurement of iron heat conductivity: Earth should have cooled in one billion years (lots of discussion about that in recent years). Easy way to reconcile these two observations is that Earth has a 20+ TW internal power generator. How??
Have CUDOs been captured: Solar system?

**Outer Moons of Jupiter**

Newly discovered moons shown in bold

Unlike the group of inner prograde moons, new prograde Valetudo has an orbit that crosses the retrogrades.

Why is Valetudo not long destroyed by in collisions?? Mybe orbit characteristics are ‘recent’ and moon stable in collision?
On asteroids of high density

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Density of asteroids

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Table 1
Compilation of the average mass (M) and volume-equivalent diameter (d) estimates (see Appendix A-C), and resulting bulk density (ρ) and macroporosity (γ) for 287 objects, with their associated uncertainties. For each object, the dynamical class (Dyn.), together with the taxonomic class (Tax., for asteroids only) and associated meteorite (Met.) class. The density estimates are ranked A–E, according to the level of confidence at which they are determined (see text). Unreliable density estimates are marked with a cross (x) and uncertainties on the macroporosity larger than 100% are listed as ±∞. References: (1) Clark et al. (2010), (2) Ockert-Bell et al. (2010), and (3) Farinellas et al. (2011). An electronic version of this table is available at https://genesis.imcce.fr/tools/public/densities.php.

33 Polyhymnia: $\rho = 75.28 \pm 9.71\text{g/cc}$. Other with high probability above $\rho_{\text{Au-U}} = 20\text{g/cc}$: 152 Atala $47.92 \pm 13.10\text{g/cc}$; & 675 Ludmilla $73.99 \pm 15.05$
Asteroids of high density
there are a few more suspects: List of anomalies/CUDO candidates:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>M $[10^{18} \text{kg}]$</th>
<th>Diameter $[\text{km}]$</th>
<th>$\rho \ [\text{g/cm}^3]$</th>
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<tbody>
<tr>
<td>33</td>
<td>Polyhymnia</td>
<td>6.20 ± 0.74</td>
<td>53.98 ± 0.91</td>
<td>75.3 ± 9.7</td>
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<td>152</td>
<td>Atala</td>
<td>5.43 ± 1.24</td>
<td>60.03 ± 3.01</td>
<td>47.9 ± 13.1</td>
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<tr>
<td>675</td>
<td>Ludmilla</td>
<td>12.0 ± 2.4</td>
<td>67.66 ± 0.95</td>
<td>74.0 ± 15.1</td>
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<td>1686</td>
<td>DeSitter</td>
<td>6.76 ± 3.18</td>
<td>30.60 ± 1.41</td>
<td>450.5 ± 221</td>
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<td>57</td>
<td>Mnemosyne</td>
<td>12.6 ± 2.4</td>
<td>113.01 ± 4.46</td>
<td>16.62 ± 3.73</td>
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<td>72</td>
<td>Feronia</td>
<td>3.32 ± 8.49</td>
<td>83.95 ± 4.02</td>
<td>10.71 ± 27.44</td>
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<td>112</td>
<td>Iphigenia</td>
<td>1.97 ± 6.78</td>
<td>71.07 ± 0.52</td>
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<td>126</td>
<td>Velleda</td>
<td>0.47 ± 5.79</td>
<td>44.79 ± 1.33</td>
<td>10.00 ± 123.00</td>
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<td>132</td>
<td>Aethra</td>
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<td>35.83 ± 6.59</td>
<td>17.09 ± 112.83</td>
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<td>148</td>
<td>Galia</td>
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<td>83.45 ± 5.07</td>
<td>16.06 ± 6.22</td>
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<td>Isabella</td>
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<td>73.70 ± 8.47</td>
<td>16.26 ± 7.65</td>
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<td>8.84 ± 29.17</td>
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<td>485</td>
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<td>1013</td>
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<td>7.50 ± 62.74</td>
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<tr>
<td>1036</td>
<td>Ganymed</td>
<td>0.167 ± 0.318</td>
<td>34.28 ± 1.38</td>
<td>7.91 ± 15.10</td>
</tr>
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</table>
Egg moon of Saturn: Methone

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

2012 November 6

Methone: Smooth Egg Moon of Saturn
Image Credit: Cassini Imaging Team, ISS, JPL, ESA, NASA

Explanation: Why is this moon shaped like a smooth egg? The robotic Cassini spacecraft completed the first flyby ever of Saturn's small moon Methone in May and discovered that the moon has no obvious craters. Craters, usually caused by impacts, have been seen on every moon, asteroid, and comet nucleus ever imaged in detail -- until now. Even the Earth and Titan have craters. The smoothness and egg-like shape of the 3-kilometer-diameter moon might be caused by Methone's surface being able to shift -- something that might occur were the moon coated by a deep pile of sub-visual rubble. If so, the most similar objects in our Solar System would include Saturn's moons Telesto, Pandora, Calypso, as well as asteroid Itokawa, all of which show sections that are unusually smooth. Methone is not entirely featureless, though, as some surface sections appear darker than others. Although flybys of Methone are difficult, interest in the nature and history of this unusual moon is sure to continue.

Low 'density' and yet surface reforms and object not blown into pieces
Comet Lovejoy survives encounter with Sun

**Figure 8.** Appearance of comet C/2011 W3 and its dust tail in an image taken with the C2 coronagraph on board the SOHO spacecraft on December 16.117 UT, or 0.105 days after perihelion. The tail, to the southeast of the Sun, seems to be completely disconnected from the comet’s head, to the west of the Sun.

**The Astrophysical Journal, 757:127 (33pp), 2012 October 1**

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**COMET C/2011 W3 (LOVEJOY): ORBIT DETERMINATION, OUTBURSTS, DISINTEGRATION OF NUCLEUS, DUST-TAIL MORPHOLOGY, AND RELATIONSHIP TO NEW CLUSTER OF BRIGHT SUNGRAZERS**

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Received 2012 May 12; accepted 2012 July 30; published 2012 September 11

**ABSTRACT**

We describe the physical and orbital properties of C/2011 W3. After surviving perihelion passage, the comet was observed to undergo major physical changes. The permanent loss of the nuclear condensation and the formation of a narrow spine tail were observed first at Malargue, Argentina, on December 20 and then systematically at Siding Spring, Australia. The process of disintegration culminated with a terminal fragmentation event on December 17.6 UT. The post-perihelion dust tail, observed for ~3 months, was the product of activity over ~2 days. The...
Comet Ison survives encounter with Sun

IMAGING COMET ISON C/2012 S1 IN THE INNER CORONA AT PERIHELION

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Received 2014 January 2; accepted 2014 February 16; published 2014 March 12

ABSTRACT

Much anticipation and speculation were building around comet ISON, or C/2012 S1, discovered on 2012 September 21 by the International Scientific Optical Network telescope in Russia, and bound for the Sun on 2013 November 28, with a closest heliocentric approach distance of 2.7 \( R_\odot \). Here we present the first white light image of the comet’s trail through the inner corona. The image was taken with a wide field Lyot-type coronagraph from the Mees Observatory on Haleakala at 19:12 UT, past its perihelion passage at 18:45 UT. The perfect match between the comet’s trail captured in the inner corona and the trail that had persisted across the field of view of 2–6 \( R_\odot \) of the Solar and Heliospheric Observatory Large Angle and Spectrometric Coronagraph Experiment/C2 coronagraph at 19:12 UT demonstrates that the comet survived its perihelion passage.
To conclude: one new idea: CUDO allows to explain

- “Disappearing” ‘giant’ meteorites
- Persistent hot-spots in middle of tectonic plates
- Dual impact/volcanic activity cooling climate events
- Young (post-cool-freezing) volcanic activity on Moon, Mars
  \(\text{(not described in detail today)}\)
- Recent large rayed crater on Mars, transfer of material to Earth
- Comets fly through Sun
- Superdense extraterrestrial bodies and other flying anomalies

Earth (all rocky bodies) seem to be punctured many times – NOTE crust puncture not possible with normal matter impactor
\[\text{e.g. Ivanov, Geology, 31 (2004)}\]
What broke-up Pangea

Fossil remains of Cynognathus, a Triassic land reptile approximately 3m long.

Fossil evidence of the Triassic land reptile Lystrosaurus.

Fossils of the fern Glossopteris, found in all of the southern continents, show that they were once joined.
Example of Strangelett Mass and Size Scales

\[ 10^{30} < A < 10^{56} \Leftrightarrow \begin{cases} 10^4 \text{ kg} < M < 10^{29} \text{ kg} \\ 10^{-20} < M/M_{\text{Earth}} < 10^5 \end{cases} \]

- Constant density: \( M \sim R^3 \)
- Density scale set by nuclear length \( R_{\text{nuc}} \sim 1 \text{ fm} \)
  (\( 10^5 \) reduction relative to normal matter atomic length \( R_{\text{atom}} \sim 1 \text{Å} \))

Normal matter asteroid | SQM “asteroid”
\[
\begin{align*}
M &\sim 10^{-5} M_{\text{Earth}} \\
R &\sim 100 \text{ km}
\end{align*}
\]
\[
\begin{align*}
M &\sim 10^{-5} M_{\text{Earth}} \\
R &\sim 1 \text{ m}
\end{align*}
\]

Compactness and high density mean...

- Gravity relevant in interactions: \( g_{\text{surf}} = \frac{GM}{R^2} = \frac{4\pi G}{3} \rho R \)
- Normal matter cannot support SQM: a strangelet “falls through”
**CUDO matter Example: Strangelets:**

**uds-symmetric matter:** $p = uud, n = ddu, \Lambda = uds$

Strangelet = piece of $n_u \simeq n_d \sim n_s$ matter, large baryon number $A$

Simple argument for (meta)stability

**Chemical equilibrium:**

\[ \mu_d = \mu_u = \mu_s \]

**Charge neutrality:**

\[ \frac{2}{3} n_u - \frac{1}{3} n_d - \frac{1}{3} n_s = 0 \]

**Compute thermodynamic potentials**

\[ \Omega_{u,d} = -\frac{\mu_{u,d}^4}{4\pi^2} \]

with massive strange quark $m_s > 0$

\[ \Omega_s = -\frac{\mu_s^4}{4\pi^2} \left( \sqrt{1 - x^2} (1 - \frac{5}{2} x^2) + \frac{3}{2} x^4 \ln(x^{-1} + \sqrt{x^{-2} - 1}) \right) \quad x = \frac{m_s}{\mu_s} \]

**Third fermi sea reduces Energy/baryon:**

\[ \frac{E/A(3 \text{ flavors})}{E/A(2 \text{ flavors})} < 1 \]
Proposed sources of Strangelets

1. Cosmological

First order phase transition to hadronic vacuum [Witten, PRD, 30(1984)]

Objects $A < 10^{55}$ evaporate at $T \simeq 50$ MeV [Alcock & Farhi, PRD, 32(1985)]

Strangeness enriched at surface $\rightarrow$ reduced emissivity of nucleons

** Quasi-equilibrium $A \sim 10^{46} \Leftrightarrow M \sim 10^{19}$ kg $= 10^{-5} M_{\text{Earth}}$ **


- Large objects $A \gtrsim 10^{23} \Omega_{\text{nug}}^3 h^6 f_N^3$ consistent with BBN
- Quark matter in nuggets does not contribute to BBN limit on $\Omega_b$

2. Strangeness in depth of compact stars

(30y track of work [Glendenning, Alcock, Alford, 1986-present])

Neutron star mergers or collisions eject fragments

Strangelet meteorites=‘Nuclearites’ considered for 30+ years:

micro-micro-CUDO impacts on Earth:
Proposed searching for
1. tracks preserved in mica
2. visible light emission
3. large scale scintillators
4. Seismic waves


all but (1) above require real time observation of impact, and we do not think this is realistic: small strangelets unstable, large CUDO’s rare.
Example of Strangelet Mass and Size Scales

Strangelet = piece of $n_u \simeq n_d \simeq n_s$ matter, large baryon number $A$


$$10^{30} < A < 10^{56} \iff \begin{cases} 10^4 \text{ kg} < M < 10^{29} \text{ kg} \\ 10^{-20} < M / M_{\text{Earth}} < 10^5 \end{cases}$$

- **Constant density**: $M \sim R^3$
- **Density scale set by nuclear length** $R_{\text{nuc}} \sim 1 \text{ fm}$ ($10^5$ reduction relative to normal matter atomic length $R_{\text{atom}} \sim 1 \text{Å}$)

Normal matter asteroid | SQM “asteroid”
---|---
$M \sim 10^{-5} M_{\text{Earth}}$ | $M \sim 10^{-5} M_{\text{Earth}}$
$R \sim 100 \text{ km}$ | $R \sim 1 \text{ m}$

---

**Compactness and high density** $\rho_{\text{nuc}} \sim 10^{15} \rho_{\text{atomic}}$ **mean...**

- **gravity relevant in interactions**: $g_{\text{surf}} = \frac{GM}{R^2} = \frac{4\pi G}{3} \rho R$

- **Matter cannot support a strangelet**: “punctures the Earth”

High Density ($\times 10^{15+}$) = Strongly Interacting Gravity

Moving fast across the following physics pages, those interested please consult these references:

- Compact ultra dense matter impactors
  http://prl.aps.org/abstract/PRL/v110/i11/e111102

- Properties of Gravitationally Bound Dark Compact Ultra Dense Objects

- Compact Ultradense Objects in the Solar System

- Planetary Impacts by Clustered Quark Matter Strangelets
  http://dx.doi.org/10.5506/APhysPolBSupp.5.381
We considered two types of DM CUDOs

Analogous to compact objects composed of SM matter:

<table>
<thead>
<tr>
<th>Fundamental fermion</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass $m_\chi \gtrsim 1$ TeV</td>
<td>Bag model vacuum pressure $B \gtrsim (1$ TeV$)^4$</td>
</tr>
<tr>
<td>supported by pressure of degenerate fermi gas</td>
<td>self-bound by interactions</td>
</tr>
<tr>
<td>analogy to white dwarf, neutron star</td>
<td>analogy to quark-star, strangelet</td>
</tr>
</tbody>
</table>

Solve for equilibrium configuration in Oppenheimer-Volkoff equations

TeV-scale Fundamental Fermi particle

\[ M_\oplus = 6 \times 10^{24} \text{ kg} = \text{Earth mass} \]

\[ M_{\text{max}} \propto m_\chi^{-2} \]

★ upper end (near ‘diagonal’ of curve are objects stable and robust in collisions
Gravitational Stability and Tidal Force

Compact: Size of object comparable to gradient of gravitational field $\Rightarrow$ Tidal force important

$$a_{\text{tidal}} = \frac{2GM_L}{r^2} \frac{1}{r} = a_{\text{surf}} \frac{R_{\text{surf}}^2}{r^2} \frac{2L}{r}$$

$\delta M/M = 10^5 - 10^{25}$

$m_\chi = 100$ TeV
50 TeV
25 TeV
10 TeV
5 TeV
2.5 TeV
1 TeV
500 GeV
250 GeV

$a_\oplus = 9.8 \text{m/s}^2$

= Earth surface

- Tidal acceleration pulls apart atoms in solids: $a_{\text{surf}} > 3.5 \times 10^{15} a_\oplus$

Dietl et al, PLB 709 (2012)

CUDOs not stopped by impact with normal visible matter
### Summary: Fundamental Fermi and Composite/Bag

<table>
<thead>
<tr>
<th>Fundamental fermion</th>
<th>Composite particle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>mass</strong> $m_\chi \gtrsim 1 \text{ TeV}$</td>
<td><strong>vacuum pressure</strong> $B \gtrsim (1 \text{ TeV})^4$</td>
</tr>
<tr>
<td>$M_{\text{max}} = 0.209 \left( \frac{1 \text{ TeV}}{m_\chi} \right)^2 M_\oplus$</td>
<td>$M_{\text{max}} = 0.014 \left( \frac{1 \text{ TeV}}{B^{1/4}} \right)^2 M_\oplus$</td>
</tr>
<tr>
<td>$R = 0.809 \left( \frac{1 \text{ TeV}}{m_\chi} \right)^2 \text{ cm}$</td>
<td>$R = 0.023 \left( \frac{1 \text{ TeV}}{B^{1/4}} \right)^2 \text{ cm}$</td>
</tr>
</tbody>
</table>

$M_\oplus = 6 \times 10^{24} \text{ kg} = \text{Earth's mass}$

- **Due to high mass scale, common** $M < \text{Earth mass}, \quad R < 1 \text{ cm}$
- **⇒ Highly compact and not too heavy**
Summary: Mass and Size Limit Examples

<table>
<thead>
<tr>
<th>Fermion mass</th>
<th>$M_{\text{max}}(M_\odot)$</th>
<th>$R_{\text{min}}$ (km)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 GeV</td>
<td>$10^{-4}$</td>
<td>1 m</td>
<td>neutralino star (cold dark matter)</td>
</tr>
<tr>
<td>1 GeV</td>
<td>1</td>
<td>10 km</td>
<td>neutron star</td>
</tr>
<tr>
<td>1 GeV/0.5 MeV</td>
<td>1</td>
<td>$10^3$ km</td>
<td>white dwarf</td>
</tr>
<tr>
<td>10 keV</td>
<td>$10^{10}$</td>
<td>$10^{11}$ km</td>
<td>sterile neutrino star</td>
</tr>
<tr>
<td>1 keV</td>
<td>$10^{12}$</td>
<td>$10^{13}$ km</td>
<td>axino star (warm dark matter)</td>
</tr>
<tr>
<td>1 eV</td>
<td>$10^{18}$</td>
<td>$10^{19}$ km</td>
<td>neutrino star</td>
</tr>
<tr>
<td>$10^{-2}$ eV</td>
<td>$10^{22}$</td>
<td>$10^{23}$ km</td>
<td>gravitino star</td>
</tr>
</tbody>
</table>

Maximum $M_{\text{max}}$ and $R_{\text{min}}$ for various cold compact stars made of a free Fermi gas

$$M_{\text{max}} = 0.627 \, M_\odot \cdot \left( \frac{1 \text{ GeV}}{m_f} \right)^2$$

$$R_{\text{min}} = 8.115 \text{ km} \cdot \left( \frac{1 \text{ GeV}}{m_f} \right)^2$$
Character of Gravit Bound Objects: Scaling Solution

If we have only \( m, M_{Pl} \) and need only 1 equation of state \( p(\rho) \)

Dimensionless...

1) pressure, density
\[
\tilde{p}(\tilde{\rho}) = m^{-4} p(\rho m^{-4})
\]

2) total mass of solution
\[
\tilde{M} = M \frac{m^2}{M_{Pl}^3}
\]

3) surface radius of solution
\[
\tilde{R} = R \frac{m^2}{M_{Pl}}
\]

TOV equations now dimensionless – Solve once!

NOT the whole story: check stability against perturbation

Oppenheimer/Serber 1936

[Narain, Schaffner-Bielich, Mishutsin, PRD 74 (2006)]
Composite with TeV confinement energy

\[ M_\oplus = 6 \times 10^{24} \text{ kg} = \text{Earth mass} \quad B = \text{bag model vacuum pressure} \]

\[ M_{\text{max}} \propto (B^{1/4})^{-2} \]


Dietl et al, PLB 709 (2012)

Tidal force destructive for \( a_{\text{surf}} > 3.5 \times 10^{15} a_\oplus \)
Collisions: a) Tidal Forces

Consider CUDO passing through normal density matter: capture for distance $R_c$ when energy gain of attached matter is greater than the kinetic energy this material must acquire

$$R_c := \frac{2GM}{v^2}$$

Matter disrupted due to differential acceleration

$$a(r - L/2) - a(r + L/2) = a_{\text{tidal}} = \frac{2GML}{r^3}$$

To compromise structural integrity,

gravitational pressure $> \text{ compressional strength}$

$$\frac{F_{\text{tidal}}}{\text{area}} = \rho L a_{\text{tidal}} > \rho c_s^2 \quad (\text{bulk modulus})$$

$\Rightarrow$ Material fails somewhere within Fracture length

$$\frac{L}{R_c} = \sqrt{2} \frac{c_s}{v} \left( \frac{r}{R_c} \right)^{3/2}$$

$c_s = \text{Bulk sound speed}$
Collisions: b) Fracture length and capture radius

Length scale: Gravitational capture radius \( R_c = \frac{2GM}{v^2} \)

\( r < R_c \) material accreted to passing CUDO
\( r > R_c \) material pulled in direction of motion, but left behind

In solid medium, material must be broken into pieces small enough to accrete

\[
\frac{L}{R_c} = \sqrt{2} \frac{c_s}{v} \left( \frac{r}{R_c} \right)^{3/2} < 1
\]

sound speed \( c_s \) representing bulk modulus (strength) of medium